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Experimental research on HEL and failure properties of alumina under impact loading

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Abstract

A series of plate impact experiments on alumina was conducted using a light gas gun in order to further investigate Hugoniot elastic limit (HEL) and failure properties of alumina under shock compression. The velocity interferometer system for any reflector (VISAR) was used to record the rear-free surface velocity histories of the alumina samples. According to the experimental results, the HELs of tested alumina samples with different thicknesses were measured, and the decay phenomenon of elastic wave in shocked alumina was studied. A phenomenological expression between HEL and thickness of sample was presented, and the causes of the decay phenomenon were discussed. The propagation of failure wave in shocked alumina was probed. The velocity and delayed time of failure wave propagation were obtained. The physical mechanism of the generation and propagation of failure was further discussed.

Keywords: Plate impact experiment; Alumina; Hugoniot elastic limit; Failure wave

1. Introduction

The interest to investigate the behavior of ceramics subjected to high velocity impact evolves mainly from their importance to manufacture the light-weight armor composites. The compressive strength and failure characteristics of ceramic armor under shock loading are the important factors for analyzing a ballistic performance against the penetrator. Understanding of the properties of the compressive strength and failure of ceramics under impact loading is essential in the design of improved impact resistant materials for dynamic structural and armor applications.

The Hugoniot elastic limit (HEL) is interpreted as the limit of elastic response and the onset of failure under dynamic uniaxial strain loading, which is used extensively in high velocity impact dynamics. During the past decades, the flyer plate impact test has been the most frequently reported experimental technique for measuring the HEL of material. The previous experimental results showed an interesting phenomenon of that the elastic precursor amplitude decreased with propagation distance in the alumina sample, which was termed as precursor decay [1–4]. However, Refs. [5,6] presented the conflicting results that no sign of such precursor decay was observed in tested alumina.

The failure wave, which is one of the most important discoveries in impact dynamics field over the last 20 years, is a new brittle failure mechanism of some brittle materials, such as glass and ceramics, etc., under compressive shock loading. It was observed by Rasorenov [7] and Kanel [8] through an observation of a small recompression signal on the free surface velocity history of shocked K19 glass. Continuing efforts have been made to confirm the existence of failure waves in other types of glasses [9–12] and ceramics, such as alumina [13,14], silicon carbide [15] and boron carbide [16]. The formation and propagation mechanisms of this failure phenomenon have been proposed over the last two decades. However, the understanding of the failure wave phenomenon is still far from complete because there are some disagreement and controversy between the available data and theoretical predictions. For example, up to now, it is not sure whether the propagating velocity of failure wave, which is a crucial parameter to characterize the failure wave phenomenon, is a constant or not under a certain dynamic loading. Refs. [7,8] reported that the failure wave velocity decreased with the increase in propagation distance in shock loaded materials. However, more researchers believed that the failure wave velocity in brittle materials is constant with the given external loading and increases with the increase in loading intensity. In this paper,

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the velocity of failure wave in shocked alumina was measured by the VISAR technique. And the formation mechanism of failure wave of alumina was further analyzed.

2. Experiment

The density of the tested alumina, ρ0, is 3.896 g/cm^3, the measured longitudinal wave velocity cl is 9.259 km/s, the shear wave velocity cs is 5.557 km/s, and the Poisson ratio v is 0.218. The calculated sound velocity corresponding to the volume compressibility of the material is

$$cb = cl\sqrt{(1+v)/3(1-v)} = 6.671\,\text{km}/\text{s}.$$

The composition of the tested alumina consists of 92.85% Al2O3, 4.89% SiO2, 0.36% CaO and 1.90% La2O3 by weight. We studied the samples in the form of disks with 40 mm in diameter and 4, 6, 8 and 10 mm in thickness. A 6 mm thick copper flyer was designed with the longitudinal wave velocity of 3490 m/s.

The double-thickness target developed in the study is shown in Fig. 1, in which two sub-targets are embedded into a two-hole target ring, with the impact surfaces of both the target ring and two sub-targets being rigorously set on one plane. The plate impact experiments under the one-dimensional strain condition were carried out on a Φ100 mm one-stage light gas gun, and two free surface velocity histories of each sub-target were recorded simultaneously by the VISAR technique. Impact velocities were measured to 1.5% accuracy using three pairs of electric signal pins and were all in the range of 439–445 m/s. So the samples were considered to undergo the same compressive state approximately.

3. Results and discussions

Fig. 2 shows the measured free surface velocity profiles of alumina samples with different thicknesses. These profiles show an initial elastic precursor wave followed by the onset of a dispersive inelastic wave which characterizes the material yielding. The onset point is denoted as HEL, which can be determined by the well-known relation

$$\sigma_{\mathrm{H}} = \frac{1}{2}\rho_0 c_l u_{\mathrm{H}} \tag{1}$$

where ρ_0 is the density of alumina, c_l is the longitudinal wave velocity, and u_{H} is the free surface velocity.

However, the free surface velocity profiles of alumina show that the transition from elastic phase to inelastic phase occurs gradually. There is no sharp distinction between the elastic part and inelastic part. The rounded transition from the elastic part to inelastic part makes the unambiguous determination of HEL value difficult. We tried to distinguish a turning point of elastic phase to inelastic phase in Fig. 2, and obtained σ_{H} of alumina using Eq. (1), as shown in Table 1. It is noted that the HEL of alumina obtained in the present study ranges from 4.41 GPa to 5.59 GPa. These data and the HELs of other aluminas [4,17,18] similar in composition are presented in Fig. 3. It is shown that the HELs of tested alumina are lower than the data presented by others. The difference in the value of σ_{H} here may be attributed to the differences in the composition, density, preparation process of samples, or the distinction of turning point.

In order to investigate the properties of HEL of alumina under shocked loading, the HELs of tested alumina were plotted against the thicknesses of samples in Fig. 4. It is found that HEL of alumina decreases with the increase in sample thickness, which is termed as the elastic precursor decay. This phenomenon is considered to be similar to the phenomenon of size effect of other brittle materials, such as concrete and rock, namely the strength of brittle material decreases with the increase in its volume. However, the physical mechanism of this phenomenon is very complex and no complete satisfactory theory exists presently. A simpler model has been proposed to describe the size effect of brittle materials under compression

$$Y = A_0 + A_1 D^{-k} \tag{2}$$

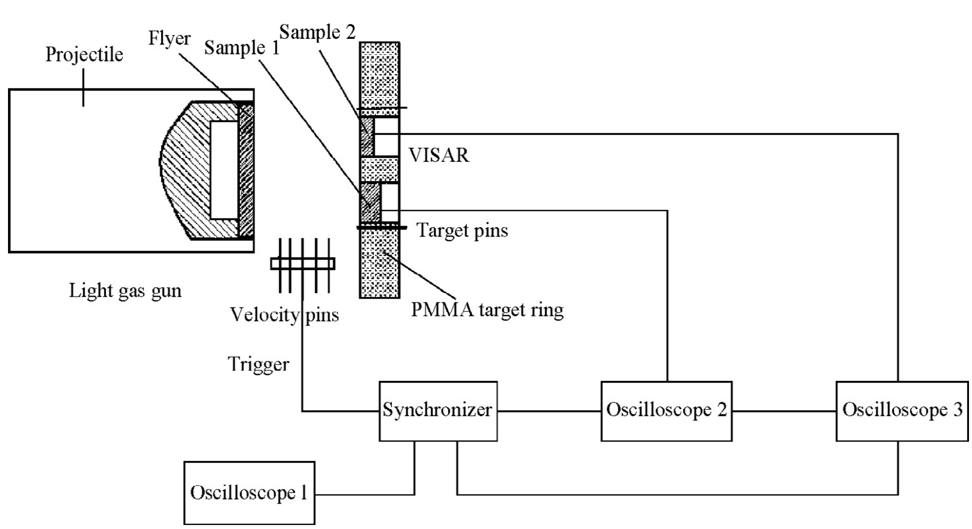

Fig. 1. Schematic diagram of double-target impact experimental setup.